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WIND TURBINE GENERATOR ROTOR BLADE CONCEPTS WITH LOW COST POTENTIAL

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Abstract

Four processes for producing blades are examined. Two use filament winding techniques and two involve filling a mold or form to produce all or part of a blade. The processes are described and a comparison is made of costs, material properties, designs and free vibration characteristics. Conclusions are made regarding the feasibility of each process to produce low cost, structurally adequate blades.

1. INTRODUCTION

The objective of the Federal Wind Energy Program, under the direction of the Department of Energy, is to accelerate the development, commercialization and utilization of reliable and economically viable wind energy systems. For large (≥ 100 kW) horizontal axis wind turbine generators (WTG's), one of the largest contributors to capital costs are the rotor blades.

NASA's Lewis Research Center has project management responsibility for studies to determine the feasibility of

several techniques for producing wind turbine blades at low cost. This paper examines four of these techniques. The materials used in the blades are not necessarily less costly than more commonly used structural materials. However, the fabrication processes are designed to greatly reduce the labor involved in producing blades. In two of the processes, all or a portion of the airfoil shape, twist and taper are produced by filament winding fiberglass on a mandrel. In the other two processes, all or a portion of the blade dimensional characteristics are obtained by filling a mold or form.

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In the first filament winding process the entire blade, i. e., spar and shell, is wound using conventional techniques. The result is a monolithic blade structure. The process was used to produce a blade 60 feet long. In the second filament winding process, a spar is wound using tape and results in 90 percent of the fibers parallel to the axis of the blade. The remainder of the blade is honeycomb stiffened fiberglass that is adhesively bonded to the spar. This process will be used to produce a blade 150 feet long. The other two processes are designed to produce 60-foot blades. One process uses foamed urethane to make the entire blade while the other uses prestressed concrete to form the blade spar. The remainder of this blade is fiberglass that is attached with mechanical fasteners to the spar. The contractors and subcontractors responsible for each blade are given in table I.

The 60-foot blades are representative of the size used on 100 kW (designated Mod-0⁽¹⁾) and 200 kW (Mod-0A) WTG's presently operating or under construction. The 150-foot blade is representative of blades for WTG's capable of generating 1500-2000 kW in winds as low as 14 mph (Mod-2). All the blades can be considered to be manufacturing prototypes and they will not be used on a WTG.

The purpose of this paper is to describe the various blades and the fabrication techniques used to manufacture them, to compare the blade costs, material properties, designs and free vibration characteristics, and to present conclusions regarding the feasibility of each process for producing blades with adequate structural integrity as well as low cost.

2. 60-FOOT FIBERGLASS BLADE

The Hamilton Standard blade design was directed at taking maximum advantage of the intrinsically low labor filament winding process. Blade shape, airfoil sections and other physical characteristics were chosen with the automated winding process in mind. The blade assembly details are shown in figure 1. The resultant blade has a length of 60 feet, a chord of 5.57 feet at the root, a chord of 1.5 feet at the tip and utilizes NACA 230XX series airfoil sections with thickness ratios ranging from 33 to 12 percent and a 12.5° twist. The design was based on the requirements for operating on Mod-0A size WTG's.

The blade, which consists of a load carrying spar and airfoil shaped shell, is fabricated completely from filament wound fiberglass, applied in continuous lengths, with winding angles selected to provide the required material properties. This approach provides a balance of material properties in all directions with good interlaminar and translaminar shear characteristics. Steel sleeves are built into the fiberglass spar to provide a smooth transfer of load from the spar to the blade retention bearing.

The spar is the main structural member of the blade and provides a major portion of the flatwise and edgewise stiffness. The retention scheme is redundant in that the total blade loading can be transferred from the spar to the rings either through the ring to spar bond joint or through the double row of bolts which pass through the rings and the spar.

The shell provides the aerodynamic planform for the blade and transfers the aerodynamic loading to the spar in

a continuous fashion. The shell properties are not a significant contributor to establishing the overall blade properties for frequency placement and the inboard end of the shell is cut off at a 45° angle to avoid load buildup in this area. The shell is filament wound directly on the spar.

The fabrication task consisted of tool or mandrel fabrication and manufacturing prototype blade fabrication. These activities were performed at the Allegany Ballistics Laboratory (ABL) of Hercules, Inc. Existing equipment at ABL was modified and new equipment was fabricated to construct a filament winding machine with the needed capacity. Figure 2(a) shows the complete filament winding machine during spar trial winding. Tool fabrication included the center steel shaft, spar mandrel formers, shell mandrel formers, shell winding offset fixture, generating disks, and mandrel removal equipment. Blade fabrication included spar winding, retention adapter sleeve bonding, shell winding, heat cure, mandrel removal and inspection.

2.1 TOOL FABRICATION

Center steel shaft. The center steel shaft was a weldment constructed of rectangular box beams, channels, and flat plates. The completed shaft as it was installed in the winding machine is shown in figure 2(b).

Spar mandrel formers. The spar mandrel formers were constructed in 45-inch lengths. Each 45-inch length consisted of four airfoil shaped plywood bulkheads held in position by wood stringers and covered with an aluminum skin. Three 45-inch lengths were assembled together with the leading edge

and trailing edge portions separated by 135-inch long wood keys which were held in place with metal rods as shown in figure 2(c). Each section was attached to the next section by steel cables to facilitate section removal.

Shell mandrel formers. The shell mandrel formers were constructed in the same manner as the spar mandrel formers with airfoil shaped plywood bulkheads, wood stringers, and aluminum skins. Positioning on the trailing edge of the spar was accomplished through the use of a slotted wood key placed over pins wound into the spar at various stations along the length. Removal was accomplished by removing the key, collapsing the section away from the face and camber sides of the shell and sliding it along the spar. Figure 2(d) shows the first three 45-inch lengths of shell mandrel formers. The blend from the blade butt to the first airfoil section at the 75-inch station was fabricated from wood blocks machined to template fit.

Shell mandrel offset fixture. An offset crank fixture was required for the shell winding operation because the spar and shell centerlines were not coincident. It is necessary during filament winding to rotate the mandrel about the geometric centerline of the part being wound. This fixture attached to and offset the spar mandrel so that the center of the shell was at the center of the winding machine drive shaft.

Generating disks. In order to minimize material scrap during filament winding parts with varying wall thicknesses, it is desirable to terminate or drop off plies at various locations along the length of the part being wound. Through the use of symmetrical generating disks on the part, it is only necessary to wind

to the disk rather than to the end of the part. Thus less material is scrapped when the unused part of the ply is cut and dropped off.

Trial winding. Final checkout of the system was accomplished by trial windings. The full spar mandrel was assembled on the center shaft and winding trials were conducted in three steps to confirm the ability of the winding machine to produce the desired filament pattern on the blade. First, the full length pattern was programmed as shown in figure 2(a). Then, the mandrel sections were removed from the tip to the 570-inch station where a generating disk was assembled. The winding pattern to the generating disk was programmed by slight modifications to the full length program. Finally, mandrel sections were removed from the 570-inch station to the 345-inch station and a generating disk assembled at the 345-inch station. The final spar pattern was programmed to complete the spar winding programs. Shell winding patterns were programmed after spar fabrication and shell mandrel assembly in the same manner as the spar patterns were programmed.

2.2 MANUFACTURING PROTOTYPE BLADE FABRICATION

The blade was fabricated as follows: the spar was wound on its mandrel and inner retention ring, the outer retention ring and shell mandrel were installed on the spar, and the shell was wound, cured and the mandrels removed. On a production tooling basis, it is anticipated that total winding time should be on the order of 6 hours. The materials used were E-glass roving and EPON 826 resin with Jeffamine D230 hardener.

Blade retention adapter sleeves. Both the inner and outer blade retention adapter sleeves were machined and then plated for corrosion protection. Under-size bolt holes were provided in the outer sleeve for use as drill bushings for drilling the holes through the fiberglass and the inner sleeve at assembly. The surface around the location of the holes on the inner sleeve was not plated to preclude plating chipping, cracking, or delamination during the subsequent drilling operation.

Spar. The spar was integrally filament wound over the inner adapter sleeve. The fiberglass thickness required between the inner and outer sleeves was achieved by interleaving fiberglass cloth with filament layers. The first plies of this cloth were applied directly over the adhesive on the inner sleeve and the first filament helical layer was wound over the cloth. Plies of fiberglass cloth were applied to the retention area between each filament helical layer. The first helical layers were wound to the 345-inch station generating disk. Figure 2(e) shows the completed windings to the 345-inch station with the spar mandrel formers assembled through the 570-inch station generating disk. The remaining spar mandrel formers were assembled and the final helical layers were wound completing the spar as shown in figure 2(f).

Outer adapter sleeve bonding. The finish wound spar was room temperature cured for 48 hours so that the material in the retention area could be machined. The spar bonding surface for the outer adapter sleeve was machined to obtain the proper bond line gap. Epoxy adhesive was applied to the spar and sleeve bonding surfaces and the sleeve was pushed onto the spar to the proper

radial location and held until the adhesive was cured. Using the pre-drilled holes in the outer sleeve as drill bushings, the adapter bolt holes were drilled and reamed to proper size as shown in figure 2(g).

Shell. The shell mandrel offset fixture was assembled and covered with a cowl-ing to provide a filament winding surface. Figure 2(h) shows the shell mandrel assembled to the spar and held in place with metal straps so that trial windings could be accomplished. Following completion of the winding trials the shell was wound to the 525-inch station as shown during winding in figure 2(i). The dark bands on the blade indicate the location of shell ply drop offs. The first and second shell helical layers were wound to the 525-inch station generating disk. The shell mandrel was then assembled to the tip and the final shell layer was wound over the full length of the blade. A 2-inch wide nylon peel ply was wound over the shell for protection and to prevent filament surface contamination during mandrel removal and shipping.

Heat cure. An insulated plywood cure hood was positioned around the finish wound blade and hot air was circulated through the hood to cure the blade at 175° F for 16 hours. Thermocouples on the blade at several locations were used to monitor material temperature to assure a proper cure cycle.

Mandrel removal. The tip of the blade and the inboard end of the shell were trimmed to allow mandrel removal. The tail stock was removed and hydraulic jacks were used to release the center steel shaft so that the blade could be pushed off the shaft. Spar mandrel formers were collapsed and

removed without difficulty. The shell mandrel became jammed during removal and it was necessary to collapse the aluminum skins on several sections before removing it completely.

The completed blade (fig. 2(j)) was inspected (X-ray, bright light, tap test and dimensional) and subjected to experimental modal analysis and structural testing at Hamilton Standard.⁽²⁾ Tap test and visual inspection of the blade showed an acceptable quality laminate. The blade was subsequently shipped to NASA for TV interference tests, and additional structural and material property testing.

3. 150-FOOT FIBERGLASS BLADE

The Kaman 150-foot wind turbine blade is an all-composite construction, consisting of a filament wound glass fiber leading edge spar, afterbody panels of paper honeycomb and fiberglass skin, and a pultruded trailing edge spline. The general arrangement is shown in figures 3(a) to (c). The afterbody panels are joined to the spar and spline by bonding. The blade is attached to the hub by a steel adaptor which is bolted to the composite spar. A steel truss carries trailing edge spline loads to the adaptor. The completed blade is expected to weigh approximately 42 000 pounds.

3.1 SPAR DESCRIPTION

The blade is an E-glass/epoxy composite, in which 90 percent of the structural fibers are oriented nearly parallel with the longitudinal axis of the blade. The spar has three-dimensional structural taper in planform, depth, and wall thickness, which makes it necessary to reduce the distribution of structural material continuously from

root to tip. Local reinforcement is provided at the blade root by interleaving $\pm 45^\circ$ glass cloth between layers of the essentially unidirectional material to achieve a more nearly isotropic structure for attachment of the root end adapter. A primary consideration in wind turbine blades is the requirement for low cost. Therefore, a well-characterized, low-temperature curing epoxy resin system was selected for spar fabrication to avoid the cost of a large high-temperature oven for the 150-foot blade. The resin system selected is Dow Chemical DER 332 resin, CIBA RD-2 diluent, and UniRoyal TONOX 6040 hardener. This resin system can be cured in 5 hours at 180°F .

Structural Composites Industries, Incorporated, under subcontract to Kaman, will use a proprietary filament winding process to fabricate the spar to the Kaman design. The process is fully automated, and is capable of depositing large quantities of composite material rapidly. It is estimated that the process could wind a 20 000-pound spar for the 150-foot blade in 8 hours, with production tooling.

3.2 MANDREL FABRICATION

The prototype spar will be wound on a low-cost steel mandrel (fig. 4(a)), which is a stressed-skin/stringer design similar to aircraft wing structures. Ribs, spaced 3 feet apart, are arranged on a central pipe to provide the airfoil shape and twist distribution. Longitudinal stringers are welded to the ribs and skin to provide sufficient bending stiffness to limit mandrel deflections, and for resistance to buckling. Three-foot wide skins, 1/8-inch thick are wrapped around the rib-stringer frame-

work and welded to ribs and adjacent skins. The skin panels are also plug-welded to the stringers. The mandrel for the prototype blade is simply supported at the ends, and has a steady-rest near midspan. A production mandrel would be designed to eliminate the steadyrest to reduce spar fabrication time.

3.3 SPAR WINDING

For the prototype spar, a half-inch thick shell will be wound on the mandrel, and cured. At this point, mandrel extraction will be attempted, up to a pre-selected limit of applied force. If the mandrel breaks loose, no further mandrel extraction effort will be required. If the mandrel does not break loose, the spar aft web will be slit with a power saw, and pried open to free it from the mandrel. Once the mandrel is free, the slit in the spar web will be closed and repaired with a spanwise doubler of $\pm 45^\circ$ glass cloth over the entire length of the aft web. The mandrel will be reinserted and the spar wall will be brought to full thickness. A layer of peel-ply cloth will be wrapped over the entire spar to facilitate removal of excess resin and to provide a good surface for subsequent bonding operations.

It is expected that future production spars would be wound to full thickness in a single stage. A smooth production mandrel would insure easy extraction, thereby eliminating the need to free the mandrel prior to reaching full thickness.

3.4 TRAILING EDGE FABRICATION

The blade afterbody will be made of prefabricated, top and bottom honeycomb panels bonded to the spar and trailing edge spline to complete the airfoil. Each honeycomb panel is laid

up on contoured tooling that conforms to the local airfoil shape, and then bonded in an autoclave. For the 150-foot blade, panel skins will be commercial grade fiberglass cloth, and the core will be resin-impregnated paper honeycomb. The panels will be 15 to 30 feet long and 2 to 6 inches thick, depending on their location in the blade. Fiberglass doublers will provide reinforcement at panel edges.

A structural trailing edge spline extends from the blade root to midspan, tapering in cross-section to conform to the airfoil trailing edge angle and blade edgewise stiffness requirements. The spline is made from E-glass/polyester pultruded planks bonded together and then shaped to the desired contour. Steel cheek plates bonded to the inboard end of the spline transmit axial loads to the root end adapter and truss.

3.5 BLADE ASSEMBLY

In assembling the blade, the afterbody panels will be bonded to the spar (after removal of the peel ply from the spar surface), and to the trailing edge spline, using a room temperature curing paste epoxy adhesive, EA 934NA. The panel-to-spar attachment is shown in figure 4(b), and the panel-to-spline attachment is shown in figure 4(c). Approximately 50 psi pneumatic pressure will be applied to the external bond lines. A continuous "T" clip will provide a tension connection of the panel inner skin to the spar aft web. A syntactic foam adhesive will be applied between the panel core and the spar to provide a shear connection between the core and spar. The steel root end adapter, figure 4(g) will be bolted to the reinforced area of the blade spar with 18 three-inch diameter bolts and five-inch

diameter bushings to achieve a uniformity low stress level in the spar bolt holes. The steel adapter is a rolled plate weldment structurally representative of a wind turbine hub adapter, but designed in this program for attachment of the blade to a static test fixture.

Although not required for the prototype, surface screening for lightning protection would be provided in fully operational rotor blades, and a neoprene guard for erosion protection. A polyurethane paint system would also be used.

4. PRESTRESSED CONCRETE BLADE STUDY

The initial investigation into the possibility of using prestressed concrete as a material for WTG blades consisted primarily of a conceptual design study. This investigation showed the concept had sufficient promise that a follow on study was initiated to fabricate a WTG blade segment 6 feet long. This section describes the blade design deemed best out of the three designs conceived and the process required to fabricate it. A schematic of the general arrangement of this blade is shown in figure 5. In addition, the fabrication of the 6-foot blade segment will be described.

4.1 CONCEPTUAL DESIGN AND MANUFACTURE

Figure 6(a) shows a typical cross section of the concrete portion of the concrete blade concept. It consists of a heavily reinforced section at the thickest portion of the airfoil and a more lightly reinforced leading edge and aft section. In addition to the prestressed rods, the concrete is reinforced with wire grid. The airfoil is completed

with a fiberglass reinforced plastic shell trailing edge. This is shown in figure 6(b).

The concept for manufacturing the concrete portion of the blade is shown in figure 6(c). A stressing jig is required for pretensioning the rods. Wire mesh is placed around the steel rods. The inside shape of the blade is formed using a retractable steel core. The outside shape is formed by hinged forms. Concrete is introduced into the bottom of the form. The form is vibrated to insure a minimum of voids.

The total weight of the rotor is reduced by limiting the concrete construction to one-half the blade length, from 35 to 85 percent span, as shown in figure 5. The calculated annual power loss from the root cut-out is less than 5 percent because the root portion of the WTG blades contribute only a small amount of power. Steel tubing is used between the hub and the beginning of the airfoil. The tip section of the blade (15 percent span) is fiberglass reinforced plastic over a steel spar.

4.2 BLADE SEGMENT MANUFACTURE

In order to determine the feasibility of the blade concept discussed in the previous section, several cast concrete blade segments will be manufactured. The segments will be 6 feet in length without twist or taper and with a cross section like that shown in figure 6(a).

The segments will be made as follows: Cores will be made of cast foam material. A core will be placed inside the concrete form and positioned with plastic standoffs. Steel rods will be positioned through bulkheads in the concrete form. For this study the rods

will not be pretensioned. Wire mesh will be positioned around the rods. After closing the hinged form, a lightweight, high strength concrete will be poured. The form will be equipped with a vibrator.

The trailing edge is made by hand lay up of resin impregnated fiberglass on a male form. A drawing of the trailing edge and the means of attachment to the concrete is shown in figure 6(b).

5. URETHANE BLADE STUDY

The urethane blade program was primarily a study of the feasibility of using urethane as a structural material in WTG blades. It concentrated on obtaining the mechanical properties of the urethane material rather than on design and fabrication of blades. However, a typical 7-foot span airfoil segment was fabricated and tested. This section describes the fabrication of the airfoil segment. The results of the material property tests are given in a subsequent section.

The blade was made using standard urethane molding techniques. One-half of the symmetric airfoil was molded at a time. A controlled amount of polyurethane resin and an isocyanate were introduced into an impingement mixer at the base of the mold as shown in figure 7(a). The mold was heated to 140° F. The components were fed into the mold at a rate of 100 pounds per minute. The mix expanded to fill the entire mold and produced a high modulus microcellular polyurethane foam structure. Cure time was approximately 2 minutes. The airfoil half-section after removal from the mold is shown in figure 7(b). Two sections were adhesively bonded together to

make the complete airfoil shown in figure 7(c).

6. COMPARISON OF BLADE CHARACTERISTICS

In this section the actual or estimated costs for producing a single blade are compared. Also, blade weights and some of the mechanical properties of each blade material are given. Section properties, weights, natural frequencies and mode shapes for the 60- and 150-foot composite blades and the concrete blade are compared.

6.1 BLADE COSTS

The most important aspect of these blade studies is cost. Without low cost potential, these blade fabrication procedures would be of little use to WTG technology. Low cost can result from use of low cost materials, low cost fabrication processes, or a combination of these two. Materials cost for the blades under consideration in this paper are compared in table II. They range from \$0.03 per pound for concrete to \$1.50 to \$2.00 per pound for epoxy resin. The cost of 2024-T3 aluminum plate is included in table II. This is the alloy used in the present Mod-0 rotor blades.

On the basis of materials cost alone, the concrete blade would have the greatest low-cost potential. In addition, the fabrication process for producing the spar is one of low cost. For the filament wound blades, the greatest contribution to material costs on a per pound basis is the epoxy resin. This cost could be reduced to about one-third of its present value by using a polyester resin. The filament winding process used to produce these blades shows promise as a low-cost

fabrication method. For the urethane blade the material cost is relatively high but the fabrication method of filling a mold to produce a blade shape is one of low cost.

The actual filament winding cost for the 60-foot blade was \$121 000. This is the cost of labor and materials only and does not include tooling costs or the cost of the blade-to-hub adapter, lightning protection or painting. The cost of the first concrete blade is estimated to be \$33 600. The materials cost in this estimate is based on actual vendor quotes. The total cost includes the blade-to-hub adapter but not tooling costs. As a basis for comparison, the present Mod-0A aluminum blades cost approximately \$200 000 each. This is the cost of a complete blade including blade-to-hub adapter, instrumentation, and ground testing.

With the savings involved with large quantity purchases and assuming a favorable learning curve, the costs of the filament wound and concrete blades should decrease when produced in larger quantities. In addition the filament winding process is amenable to automated control and the potential savings associated with this.

6.2 MATERIAL PROPERTIES

60-Foot composite blade. In the 60-foot composite blade, the design filament orientation ranged from $\pm 20^\circ$ to $\pm 30^\circ$ in the spar and from $\pm 25^\circ$ to $\pm 35^\circ$ in the shell. The resin used was EPON 826 with Jeffamine D230 hardener. At present, extensive material property data is not available for this system but additional testing is planned. Some room temperature test results for material with a filament angle of $\pm 30^\circ$ are given in table III.

150-Foot composite blade. Some mechanical properties obtained for the material used in the 150-foot composite blade are also given in table III for two resin contents. The higher resin content is typical of that obtained where the radius of curvature of the blade is large while the lower is typical of a small radius of curvature. The resin system was DER 332 with RD-2 diluent and Tonox 6040 hardener. The material was cured at 180° F for 5 hours.

Comparing the properties in table III, it can be seen that the process used for the 150-foot blade results in a material with superior longitudinal strength and stiffness. However, this beneficial result is accompanied with reduced transverse and inplane (intralaminar) shear properties.

Concrete blade. No material property tests were conducted in the concrete blade program. However, the mechanical properties of the constituents of prestressed concrete are well known and summarized in table IV. The overall steel volume content of the spar is about 15 percent.

Urethane blade. The properties of nine different urethane formulations were determined. Four were microcellular foams and five were rigid foams. Test specimens were made by Goodyear Tire and Rubber Research Laboratories while testing was done by the University of Akron. The properties determined include density, tensile strength, compressive strength, shear strength, bearing strength, impact strength, creep resistance, Poisson's ratio, and flexural modulus. Also determined were the effects of fatigue and temperature. Here, the results obtained from the most promising

material for WTG blades, i. e., the one with the highest flexural modulus, will be examined.

A summary of the properties obtained for the high modulus urethane are given in table V. On the positive side are density and strength. The ultimate strength to density ratio is 159 000 inches. This compares to a yield strength to density ratio of 124 000 inches for some structural steels. There are several factors on the negative side. While the formulation resulted in one of the highest values of modulus obtained to date for foamed urethane, it was still not high enough to avoid the requirement of additional stiffening with steel to produce a satisfactory blade. In addition, the lack of ductility in the material, as exemplified by low elongation and impact strength, makes brittle fracture at points of stress concentration and flaw growth under cyclic loading real possibilities. It is therefore concluded that it would not be feasible to fabricate Mod-0 size WTG blades from unreinforced urethane.

6.3 SECTION PROPERTIES AND WEIGHTS

The distribution of flatwise bending stiffness, chordwise bending stiffness and weight can be compared in figures 8(a) to (c), respectively, for the two fiberglass/epoxy blades and the concrete blade. Note that the 150-foot fiberglass/epoxy blade has a different scale than the two 60-foot blades on all three figures. The stiffness values for the 60-foot fiberglass/epoxy composite blade were calculated from the actual dimensions of the blade. For the other two blades the values are design values. The step changes in the plots for

the concrete blades take place where the prestress bars are stepped out.

Weights for the 60-foot blades are compared in table VI. The table includes a very preliminary estimate of the weight of a steel reinforced urethane blade. The Mod-0 and -0A aluminum blade weights are also included in the table as a basis for comparison. As designed, fiberglass/epoxy blades are expected to weigh about the same as the Mod-0A aluminum blade. However, the final as-fabricated weight of the spar and shell of the composite blade was 46 percent greater than the design weight due to manufacturing problems. With the knowledge gained from fabricating this blade, it is expected that the weight of future blades would meet the design weight.

The design weight of the concrete blade is about 2.5 times that of the aluminum blade. While a small increase in blade weight would have little or no impact on the remainder of the WTG system, a 250 percent increase would require a redesign of critical blade pitch and drive train components and would increase the weight of other parts such as the tower. Therefore, the possibility of increased cost in other parts of the WTG must be taken into account in determining the cost benefit of using concrete blades.

The design weight of the urethane blade is 50 percent greater than the aluminum blade. This design weight includes the weight of steel required to increase the stiffness of the blade. A weight increase of this size may also require redesign of certain system components.

6.4 NATURAL FREQUENCIES AND MODE SHAPES

Natural frequencies and mode shapes for the two fiberglass/epoxy blades and the concrete blade were obtained using a finite element model of each blade. The blades were modeled using bar elements in the NASTRAN computer code. Element properties were obtained from the stiffness and weight distributions presented in the previous section.

Blade natural frequencies presented in the form of interference plots (Campbell diagrams) are given in figures 9(a) to (c) for the 60- and 150-foot composite blades and concrete blade, respectively. For all three blades the first flatwise frequency is well placed between integer multiples of the design rotational speed, P .

Natural frequencies for the 60-foot composite blade were determined experimentally by Hamilton Standard.⁽²⁾ Table VII compares the experimental results with those predicted by the NASTRAN model and a Hamilton Standard finite element model of the blade. In general the agreement between the predicted and measured results is good. However, the flatwise frequencies predicted by the NASTRAN model are about 15 percent low indicating an underestimation of the flatwise bending stiffness.

The first flatwise and first edgewise natural frequencies for the Mod-0 aluminum blades as determined by test⁽³⁾ are 1.73 Hz and 2.66 Hz, respectively. These compare to 1.53 Hz and 2.63 Hz for the composite blade (see table VII). The edgewise natural frequencies of these two blades are nearly identical while the composite blade flatwise frequency is about 12 percent lower.

Predicted first flatwise and first edge-wise mode shapes for the three blades at design rotational speed are shown in figures 10 to 12. As shown, centrifugal stiffening has a slight effect on the first flatwise mode shape. The first edge-wise mode shape is essentially unaffected by centrifugal stiffening.

7. CONCLUDING REMARKS

All the blades investigated in this paper have low cost potential. However, at this time actual low cost has yet to be demonstrated for all the blades. This section summarizes the results and conclusions specific to each blade.

60-Foot Fiberglass/Epoxy Blade

Of the four blades investigated this is the only one where, at the time of writing, the fabrication process has been demonstrated on a full size blade. Tests of this blade have demonstrated adequate strength and stiffness. Because both the spar and shell are filament wound, maximum advantage is taken of the filament winding process with its potential for low cost. The design weight of this blade is the same as an equivalent aluminum blade. However, weight control may be a problem.

150-Foot Fiberglass/Epoxy Blade

The process used should produce blades with improved strength and stiffness because in the spar 90 percent of the fibers resist the major bending moment. The process also has the ability to wind material at a very rapid rate. However, the blade trailing edge must be fabricated and attached to the spar by nonfilament winding processes. The feasibility of this process in producing a full size blade is yet to be demonstrated.

60-Foot Prestressed Concrete Blade

Because of the low cost materials used in the process, this blade has the greatest potential for low cost. Design studies have shown the blade to have adequate strength and stiffness. However, the high weight of this blade will require greater weight (and therefore, cost) in other parts of the WTG. In addition, the fabrication process has yet to be demonstrated.

Urethane Blade

The fabrication process feasibility has been demonstrated on a short blade segment. However, material property tests have shown that the stiffness and ductility of the material are too low for it to be considered a feasible WTG blade material without significant reinforcement. The weight of a steel reinforced blade is estimated to be 50 percent greater than an aluminum blade.

8. REFERENCES

1. Puthoff, Richard L.: Fabrication and Assembly of the ERDA/NASA 100-Kilowatt Experimental Wind Turbine. NASA TM X-3390, 1976.
2. Griffiee, D. G.; More, E. R.; and Pinter, W. H.: Mod-0 Wind Turbine Composite Material Manufacturing Prototype Blade Inspection and Testing. HSER 7293, 1977.
3. Donham, R. E.; Schmidt, J.; and Linscott, B. S.: 100-kW Hingeless Metal Wind Turbine Blade Design, Analysis, and Fabrication. Presented at the 31st Annual National Forum of the American Helicopter Society (Washington, D.C.), May 1975.

9. BIOGRAPHIES

T. L. SULLIVAN

Mr. Sullivan is presently with the Wind Turbine Analysis Section of the Wind Energy Project Office where he has been since 1976. He received his B. S. in Aeronautical Engineering (1959) from the University of Detroit, and M. S. (1960) and engineer's degree (1961) in Aeronautics from the California Institute of Technology. Prior to joining the Wind Energy Project Office his work at NASA involved the mechanical property characterization of and mechanical test development for advanced composite materials. He is a member of Sigma Xi and the Society for Experimental Stress Analysis.

T. P. CAHILL

Mr. Cahill is presently with the Research and Technology Section of the Wind Energy Project Office where he has been since 1975. He is manager of supporting research and technology wind turbine blade programs. He holds a B. S. degree in Civil Engineering from Carnegie Mellon University and has done graduate work in structural engineering at Case Institute of Technology. Prior to joining the Wind Energy Project Office he was associated with the Atlas, Centaur and Titan launch vehicle programs at Lewis for 13 years and for 6 years was the project manager in charge of the development, test and flight of the Centaur Standard Shroud, a large jettisonable fairing developed for the Viking and Helios missions.

D. G. GRIFFEE, JR.

Mr. Griffiee has been with Hamilton Standard Division of United Technologies Corporation for 10 years and is present-

ly a Senior Experimental Engineer. He received a B. S. in Mechanical Engineering from the University of Maine in 1967 and a M. S. in Mechanical Engineering from Rensselaer Polytechnic Institute in 1972. His experience at Hamilton Standard has been in the design, development and testing of composite material structures.

H. W. GEWEHR

Mr. Gewehr is program manager for the 150-foot fiberglass wind turbine blade program. He holds B. S. and M. S. degrees in Aeronautical Engineering from Massachusetts Institute of Technology and an M. S. degree in Management from Rensselaer Polytechnic Institute. In his 18 years at Kaman, he has functioned as test engineer and project engineer on many helicopter rotor development programs. More recently, in wind energy work, he has directed contractual and IRAD wind turbine rotor studies.

TABLE I. WTG BLADE CONTRACTORS

Blade type	Prime contractor	Subcontractor
60-Foot fiberglass/epoxy ^a	Hamilton Standard	Hercules, Inc. (ABL)
60-Foot concrete ^b	Tuthill Pump Co. of Calif. (formerly Hallikainen Assoc.)	Paragon Pacific, Inc.
60-Foot urethane ^b	Concept Development Inst.	Univ. of Akron
150-Foot fiberglass/epoxy ^a	Kaman Aerospace	Structural Composites Industries, Inc.

^aContract includes fabrication of manufacturing prototype.

^bStudy and blade segment manufacture contract only.

TABLE II. WTG BLADE MATERIAL COSTS

Material	Cost, \$/lb
Urethane foam	~1.00
Concrete (high strength)	.03
Prestressing rod (T-1 steel)	.46
Fiberglass, E-glass roving	.50
Fiberglass, E-glass tape	.65
Epoxy	1.50 - 2.00
Aluminum plate (2024-T3)	1.15

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TABLE III. REPRESENTATIVE FIBERGLASS/EPOXY
LONGITUDINAL MECHANICAL PROPERTIES

[Room temperature.]

Property	60-Foot blade material ^a	150-Foot blade material ^b	
		35% resin ^c	20% resin ^c
Ultimate strength, ksi			
Tension	42.2	53.2	63.4
Compression	-----	63.5	66.5
Ultimate strain, percent			
Tension	-----	1.00	1.18
Modulus, 10 ⁶ psi			
Tension	3.56	5.09	6.08
Compression	-----	4.41	5.00
Poisson's ratio	-----	.331	.323
Interlaminar shear strength, ksi	4.43	6.73	6.50

^aConventional filament winding process ($\pm 30^\circ$ fiber angle).

^bTape winding process (90% 0° and 10% 90° fiber angles).

^cBy weight.

TABLE IV. TYPICAL PROPERTIES OF
CONSTITUENTS OF PRESTRESSED CONCRETE

Property	Constituent	
	Steel ^a	Concrete ^b
Yield strength, ksi	100	---
Ultimate strength, ksi	115	7.5
Modulus of elasticity, 10 ⁶ psi	29	3

^aT-1 steel.

^bCompression.

TABLE V. TYPICAL PROPERTIES OF HIGH
MODULUS RIGID FOAM URETHANE

Density, lb/in ³	0.038
Tensile strength, psi	6050
Elongation to failure, percent	~3.0
Flexural strength, ^a psi	~11 300
Flexural modulus, psi	^a 57 000
Poisson's ratio	0.365
Notched Izod impact strength, lb/in	0.53

^aAssumes bending stress at ultimate load varies linearly from neutral axis.

TABLE VI. COMPARISON OF WEIGHT FOR
60-FOOT WTG BLADES

Blade type	Blade weight, lb	
	As designed	As fabricated
Fiberglass/epoxy		
Type I design		
Spar and shell	1470	2145
Complete blade	2277	----
Type II design ^a		
Spar and shell	1787	----
Complete blade	2400	----
Prestressed concrete	4900	----
Concrete	1860	----
Steel	2755	----
Fiberglass	285	----
Urethane (reinforced) ^b	3010	----
Urethane	1830	----
Steel	1180	
Aluminum		
Mod-0	----	2000
Mod-0A	----	2360

^aType II design eliminated spar bulkhead and increased spar wall thickness.

^bDoes not include blade-to-hub adapter.

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TABLE VII. COMPARISON OF PREDICTED AND
MEASURED NATURAL FREQUENCIES FOR
60-FOOT COMPOSITE BLADE (0 rpm)

Mode	Predicted frequency, Hz		Measured frequency, Hz
	NASA model	Hamilton Standard model	
First flatwise	1.32	1.45	1.53
Second flatwise	3.49	3.73	4.05
Third flatwise	7.33	8.08	8.59
First edgewise	2.51	2.51	2.63
Second edgewise	9.65	9.86	9.36
Third edgewise	24.71	24.75	22.38
First torsion	29.19	28.59	29.26

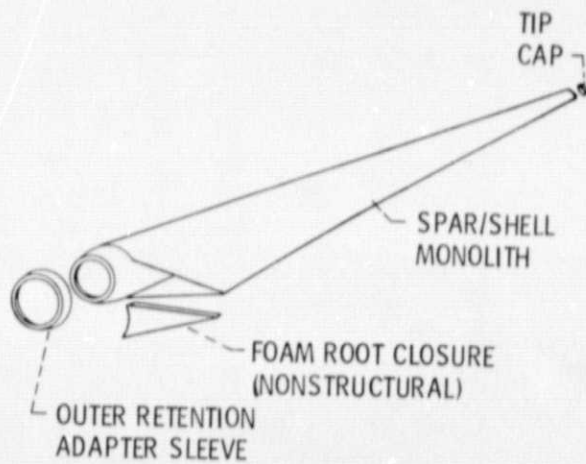
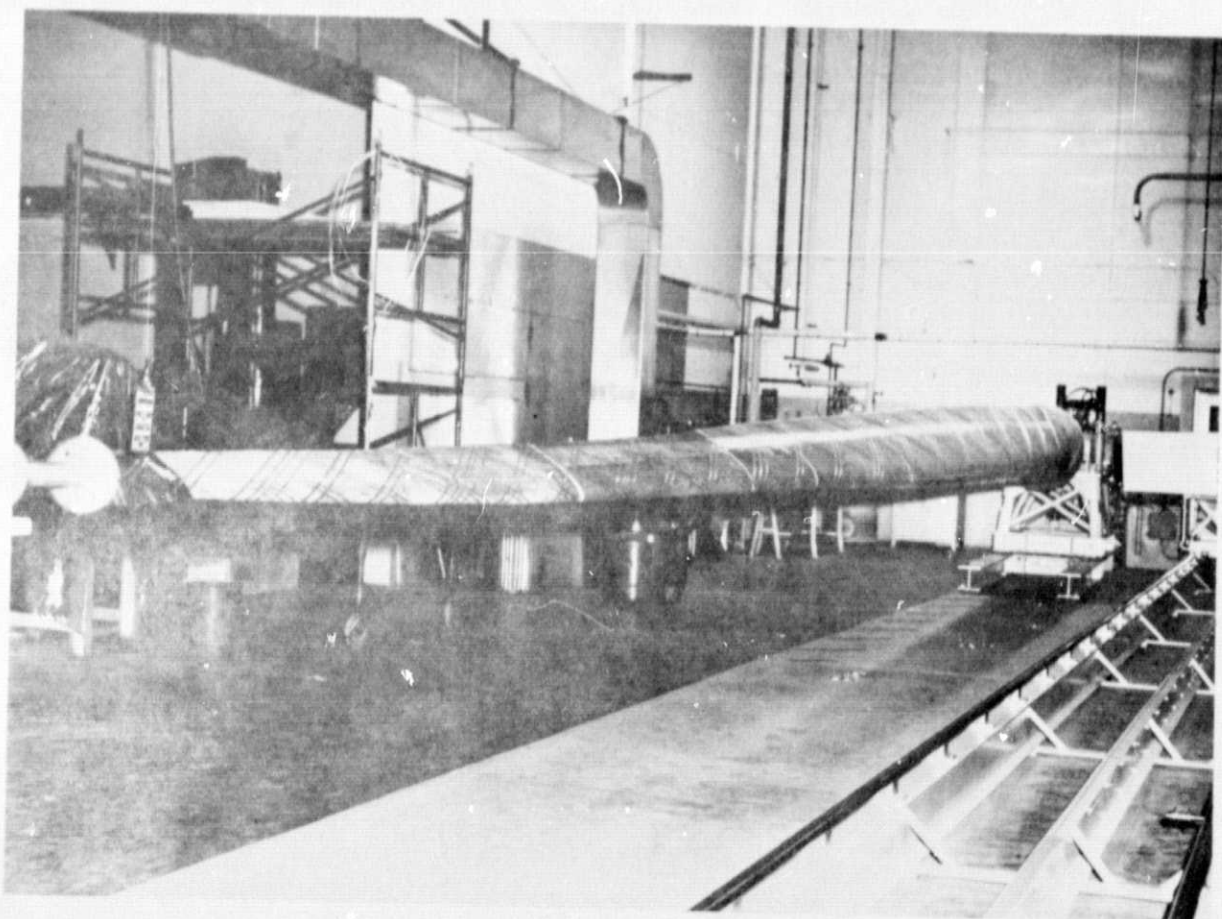


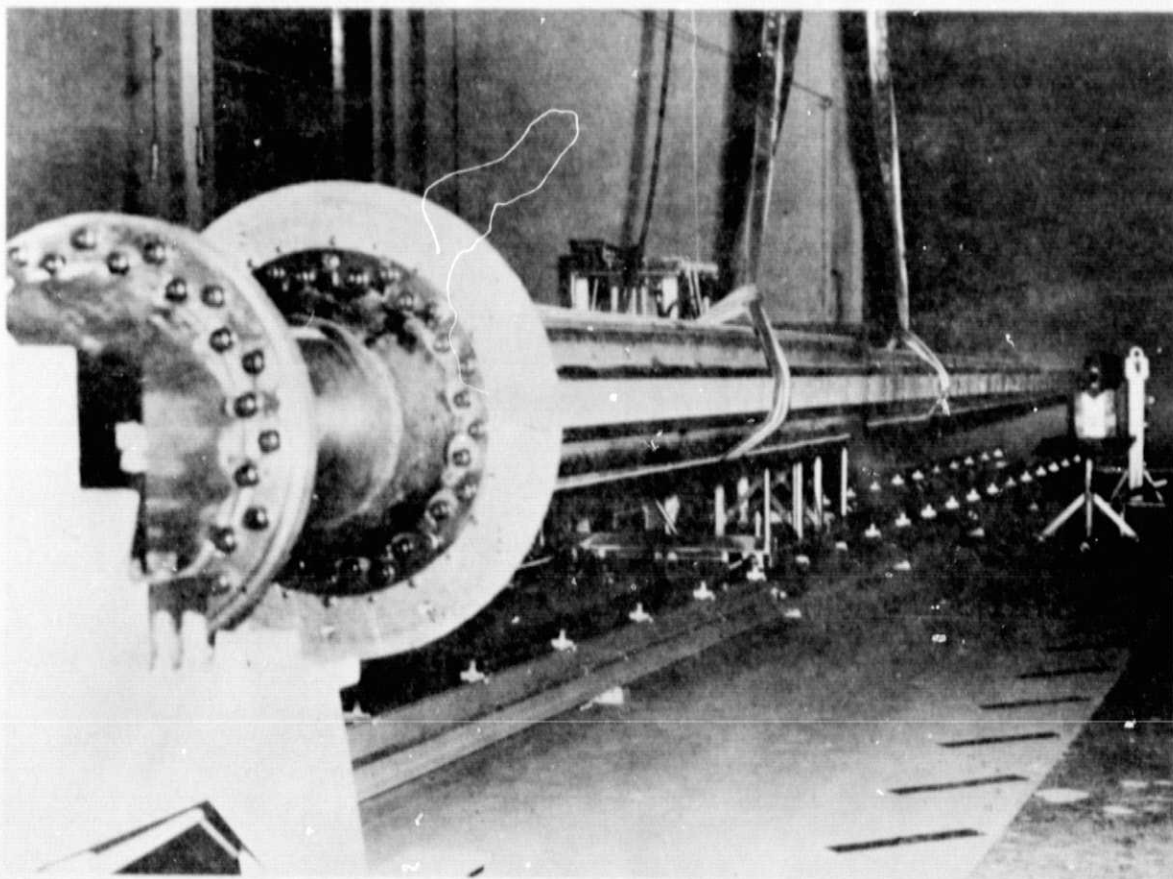
Figure 1. - 60-Foot filament wound blade assembly details.



(a) FILAMENT WINDING FACILITY AND TRIAL SPAR WINDING.

Figure 2. - 60-Foot filament wound blade fabrication procedure.

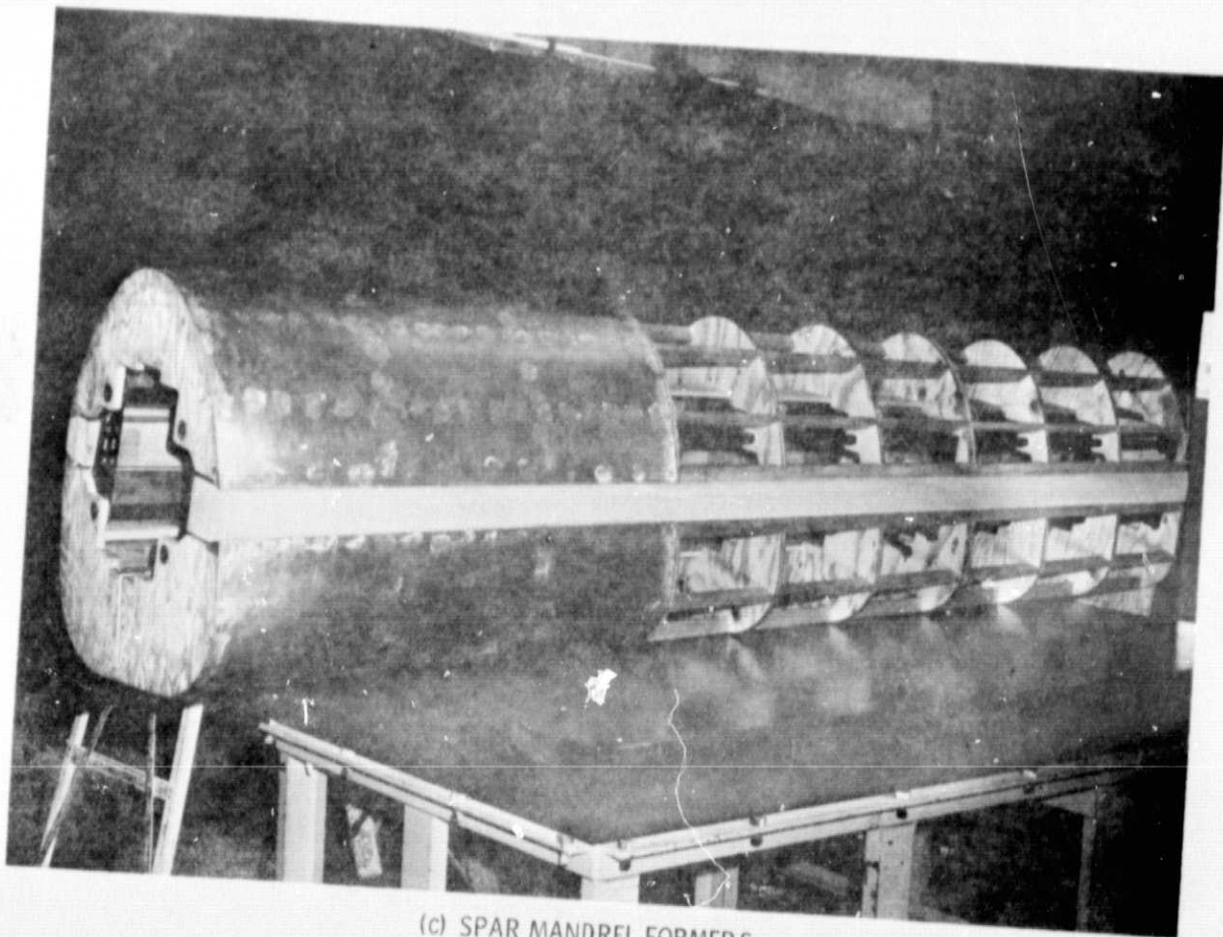
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(b) MANDREL CENTER SHAFT.

Figure 2. - Continued.

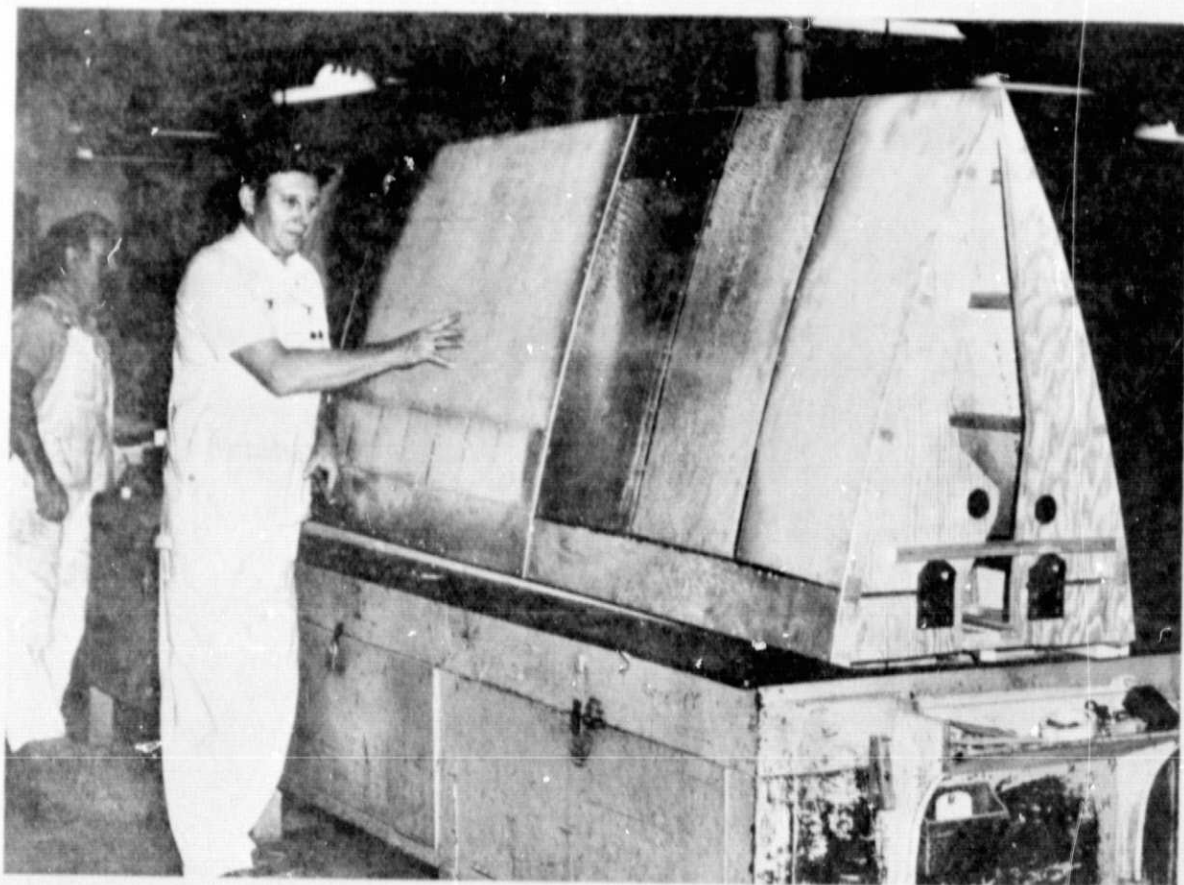
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(c) SPAR MANDREL FORMERS.

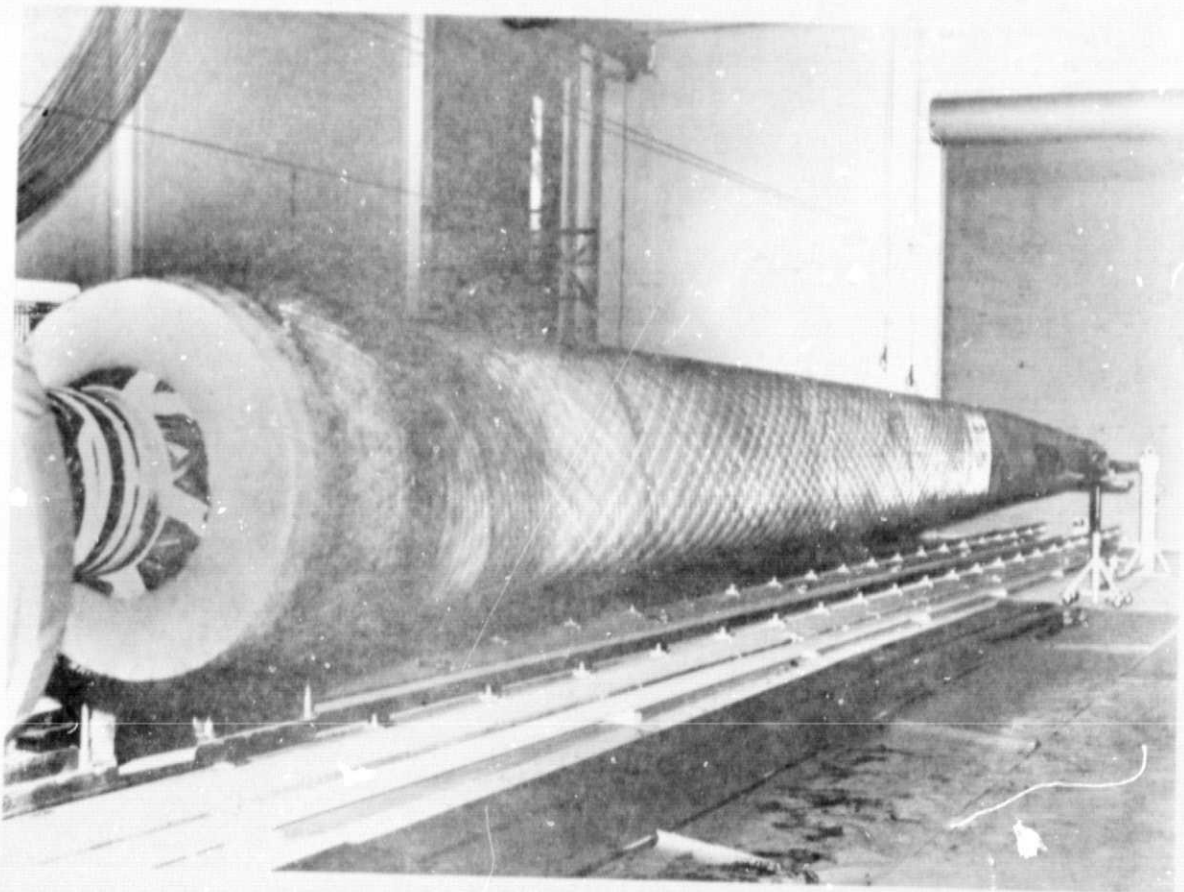
Figure 2. - Continued.

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(d) SHELL MANDREL FORMERS.

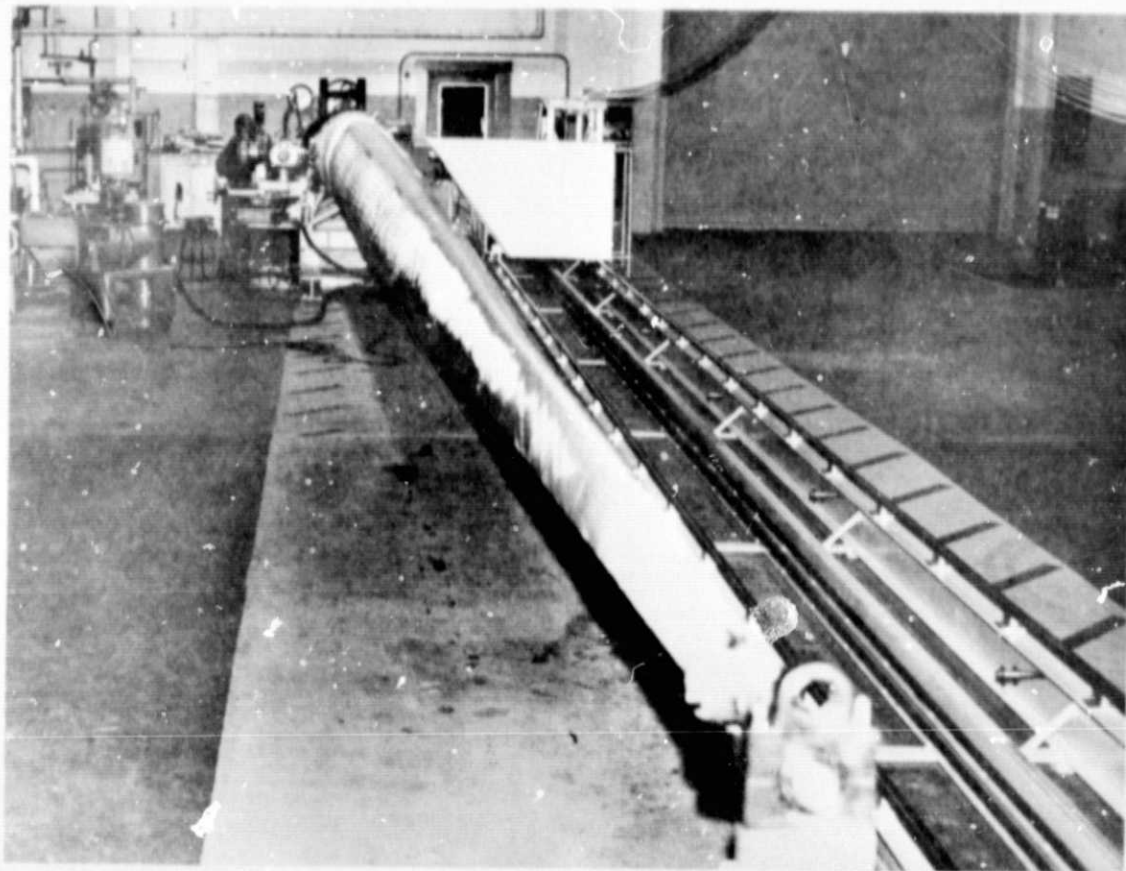
Figure 2. - Continued.



(e) SPAR COMPLETED TO 345-INCH STATION.

Figure 2. - Continued.

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(f) COMPLETED SPAR.

Figure 2. - Continued.

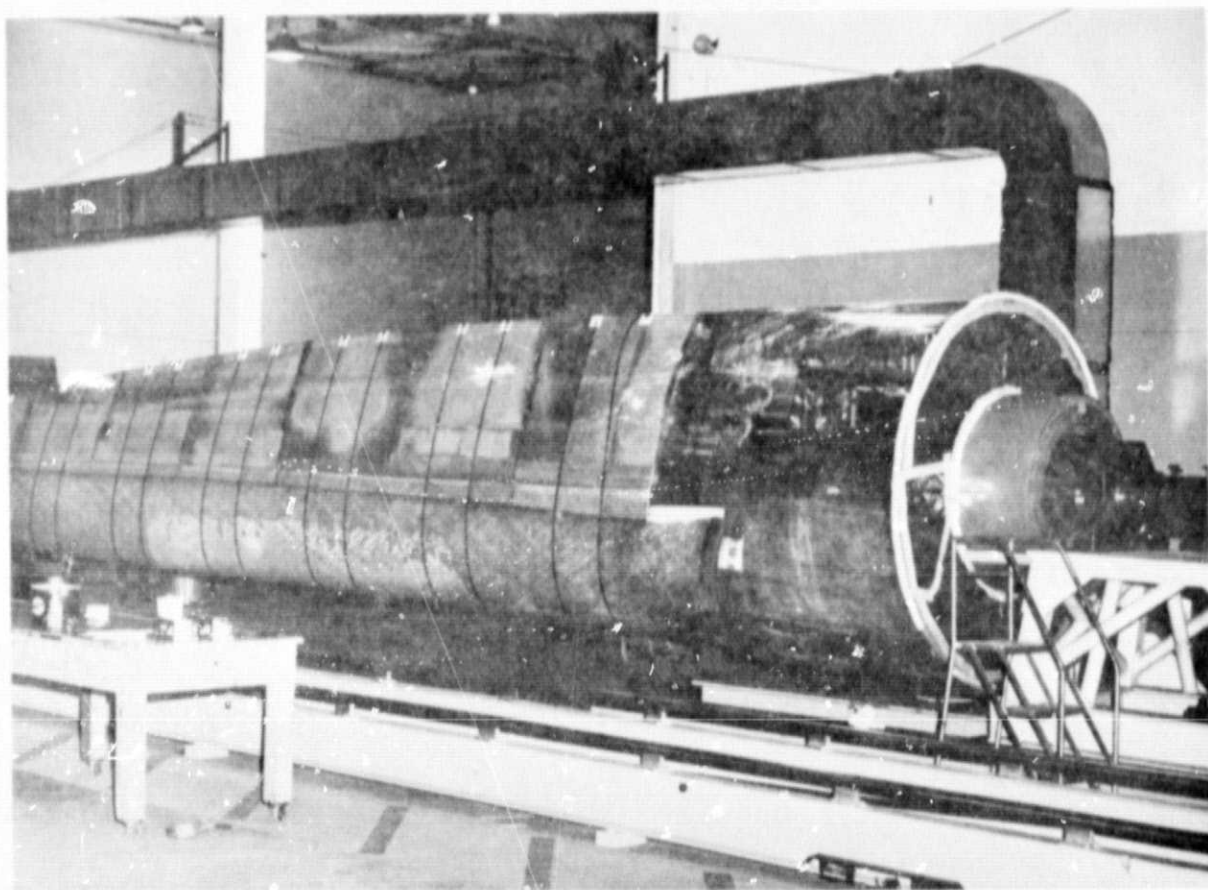
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(g) DRILLING OF RETENTION ADAPTER SLEEVE BOLT HOLES.

Figure 2. - Continued.

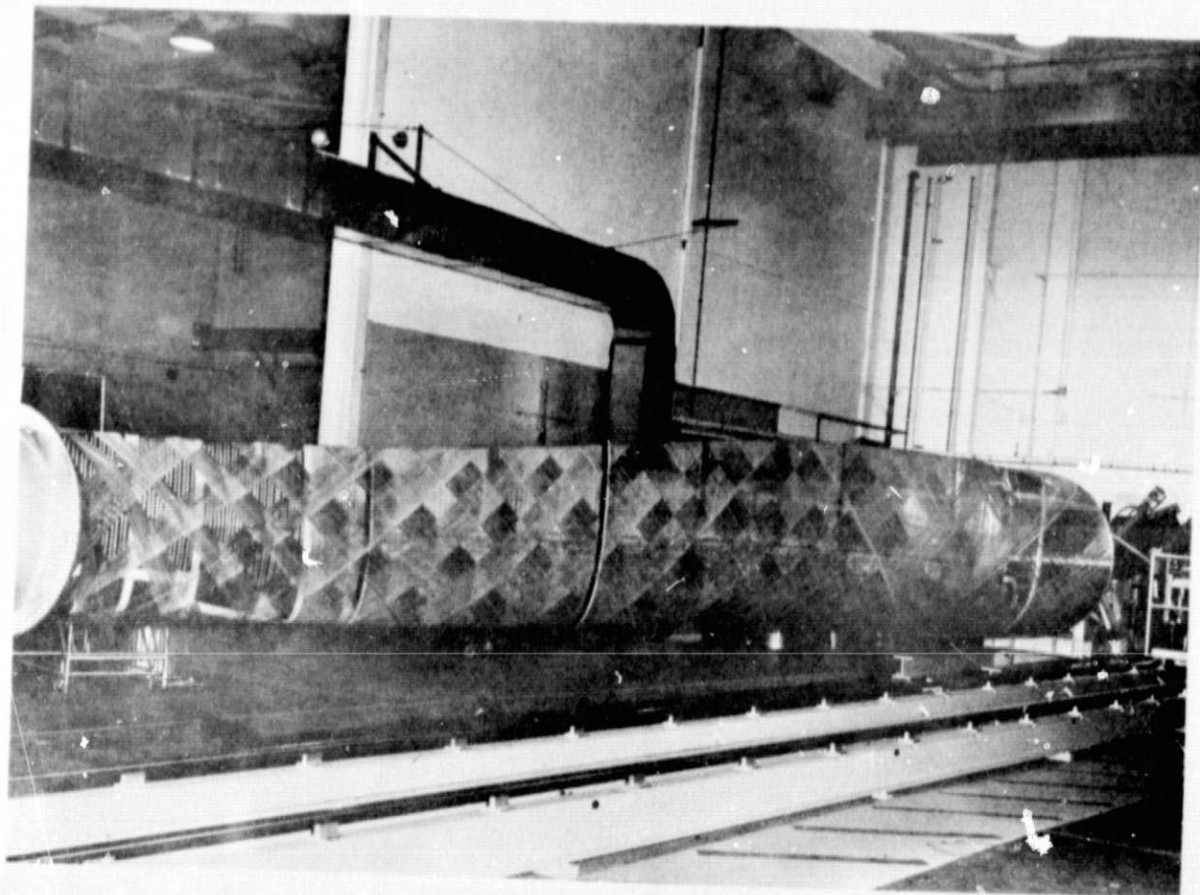
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(n) SHELL MANDREL ASSEMBLY.

Figure 2. - Continued.

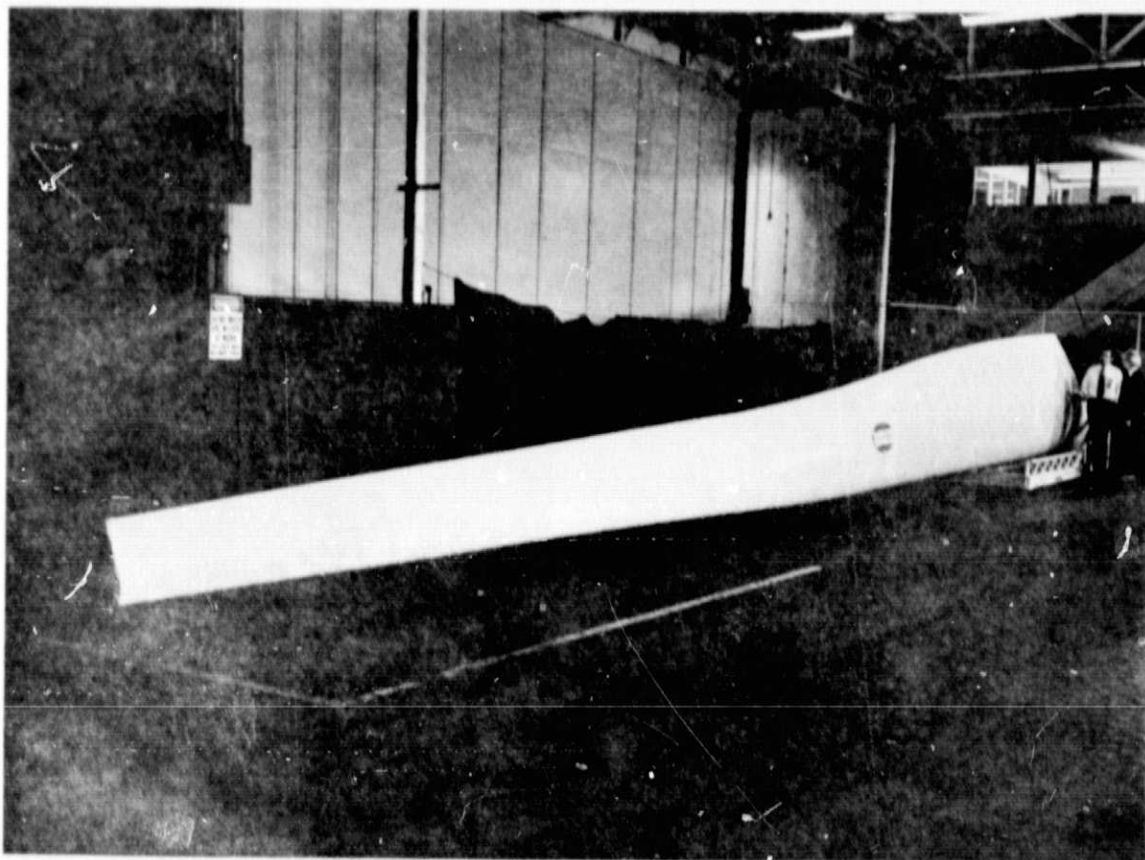
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(i) PARTIALLY COMPLETED SHELL WINDINGS.

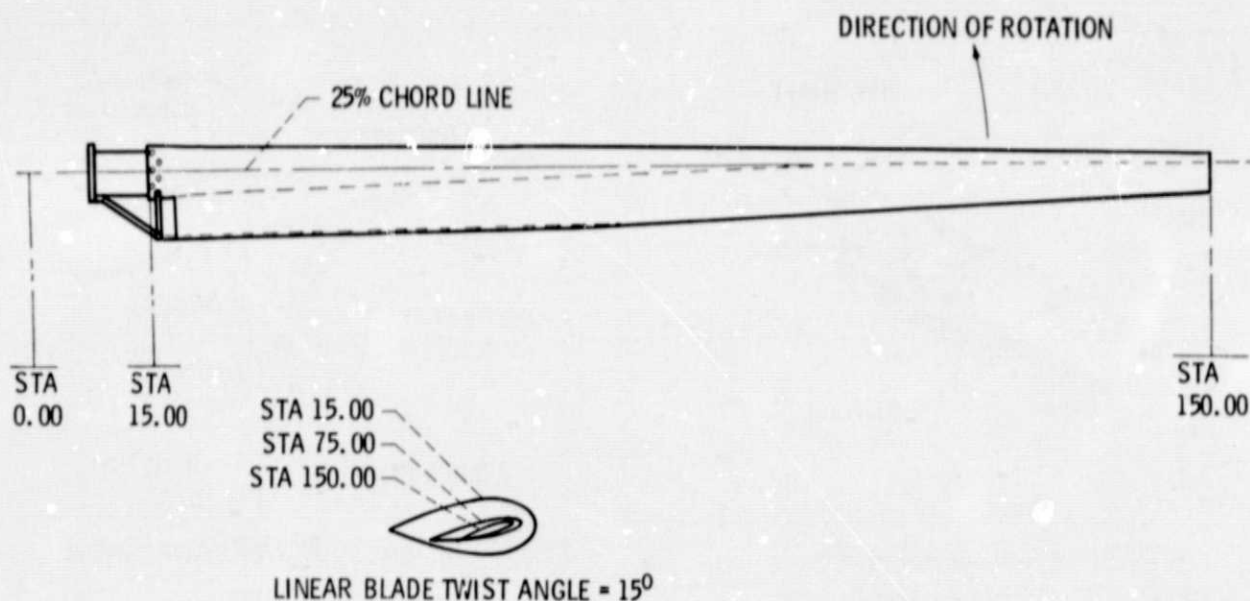
Figure 2. - Continued.

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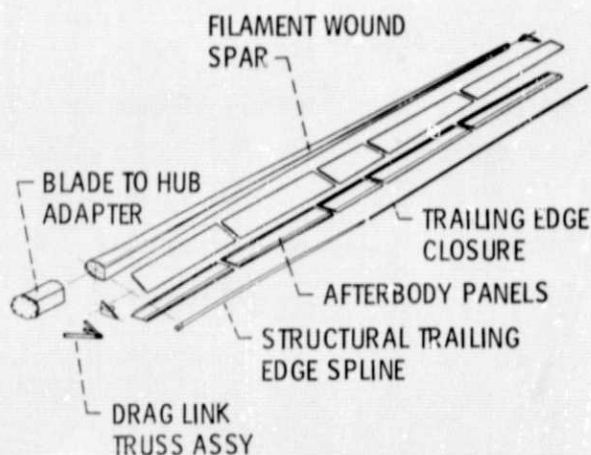
(j) FINISHED WOUND BLADE.

Figure 2. - Concluded.



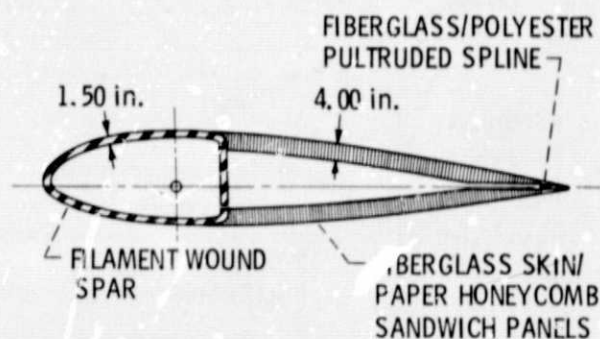
(a) BLADE PLANFORM.

Figure 3. - 150-Foot blade general arrangement.



(b) COMPONENT PARTS.

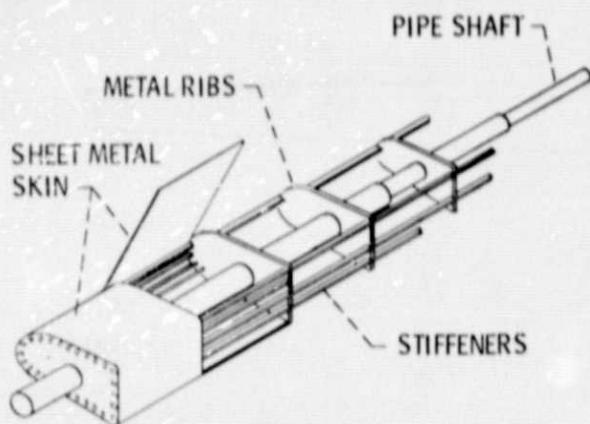
Figure 3. - Continued.



(c) MID-SPAN SECTION.

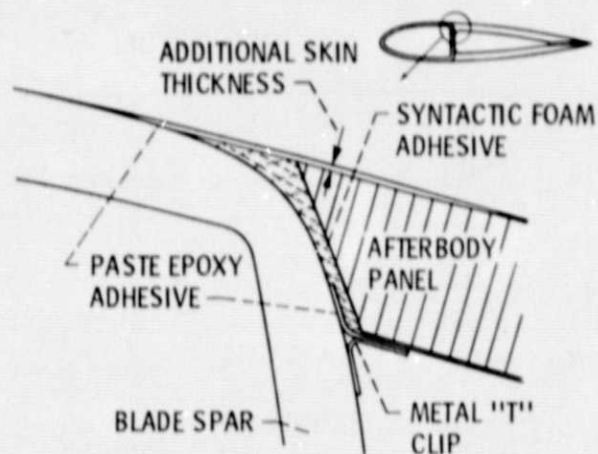
Figure 3. - Concluded.

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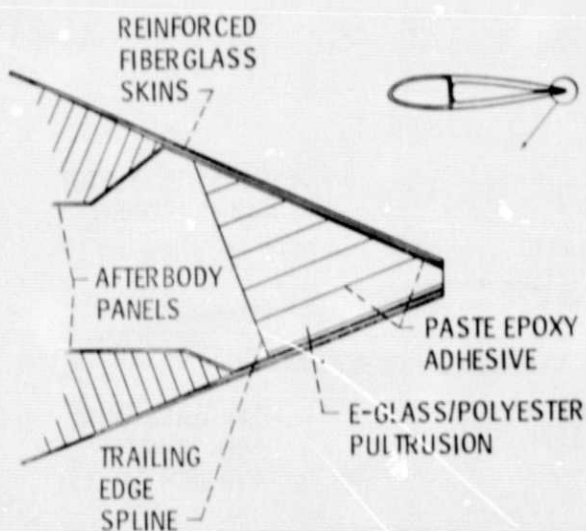
(a) SPAR MANDREL FABRICATION.

Figure 4. - 150-Foot blade assembly details.



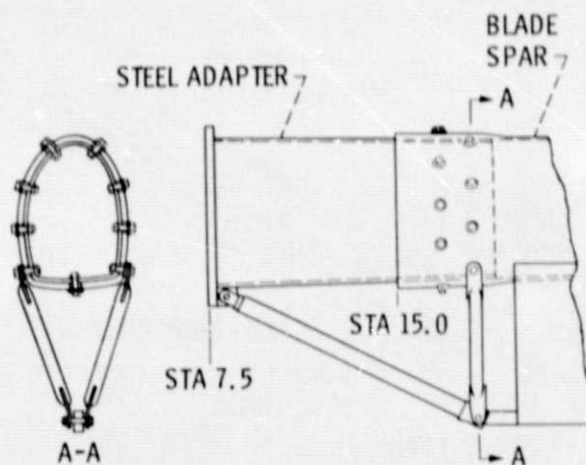
(b) SPAR TO AFTERBODY PANEL ATTACHMENT.

Figure 4. - Continued.



(c) TRAILING EDGE SPLINE AND AFTERBODY PANEL ATTACHMENT (ROOT-END AREA).

Figure 4. - Continued.



(d) BLADE ROOT END ADAPTER ATTACHMENT.

Figure 4. - Concluded.

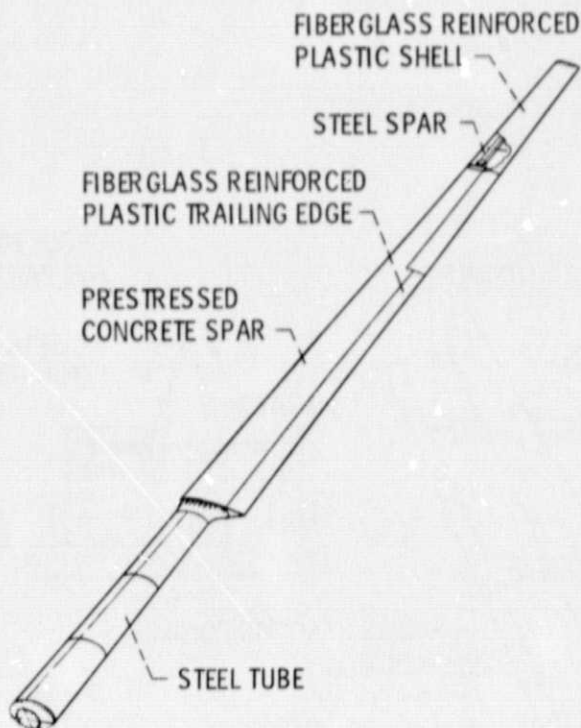
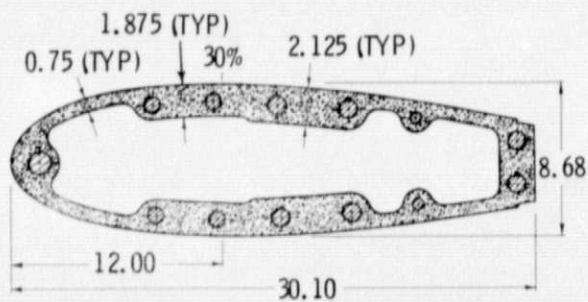


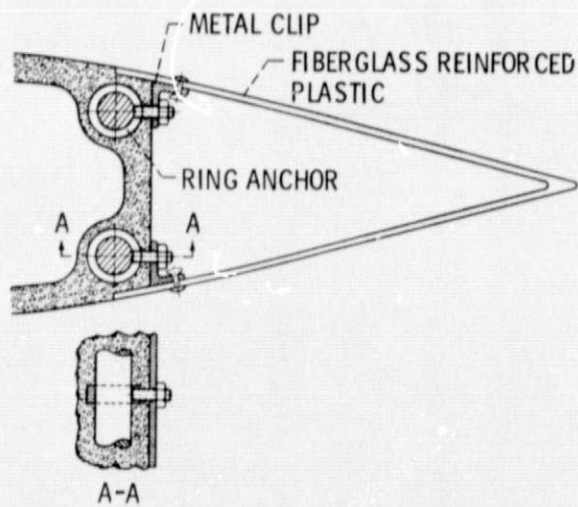
Figure 5. - 60-Foot concrete blade concept.

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(a) TYPICAL SPAR CROSS SECTION
(DIMENSIONS IN in.).

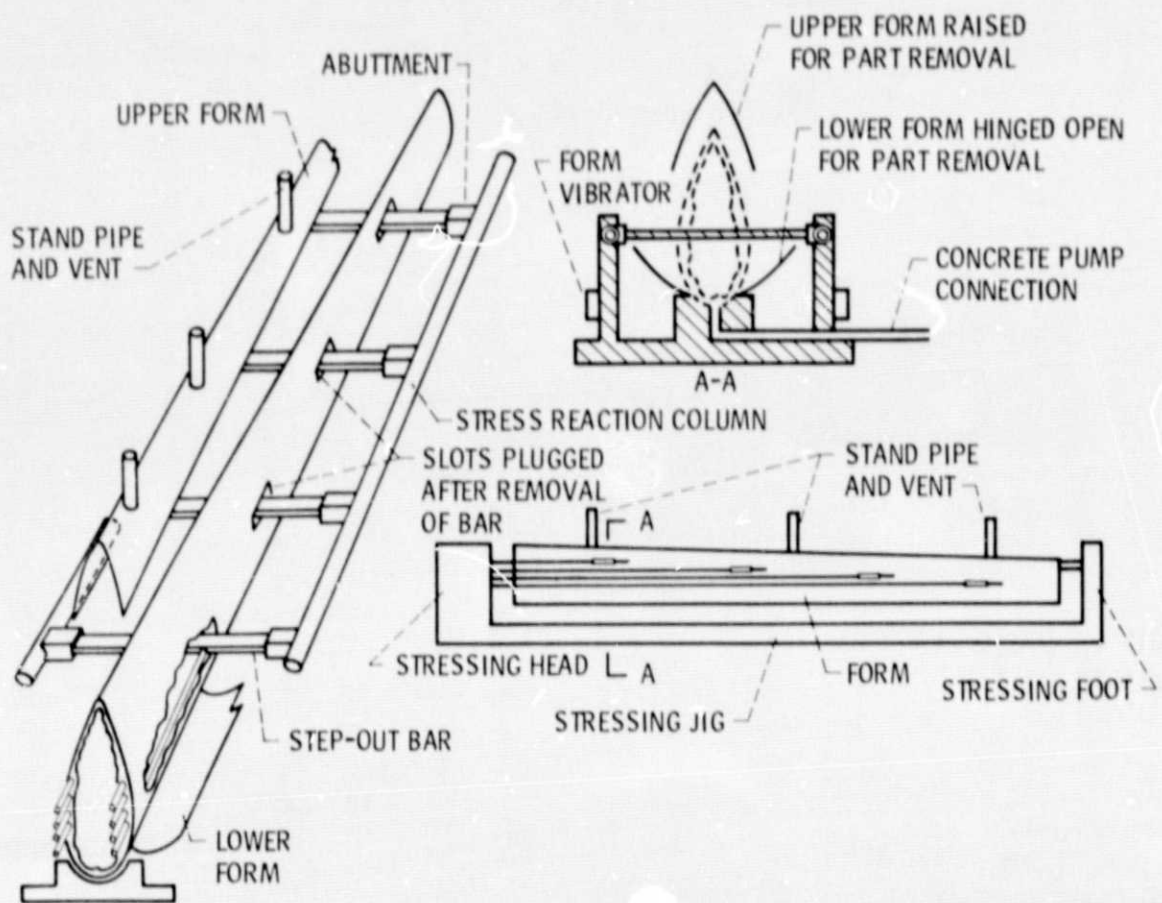
Figure 6. - 60-Foot concrete blade design, assembly,
and spar manufacturing details.



(b) TRAILING EDGE ATTACHMENT METHOD.

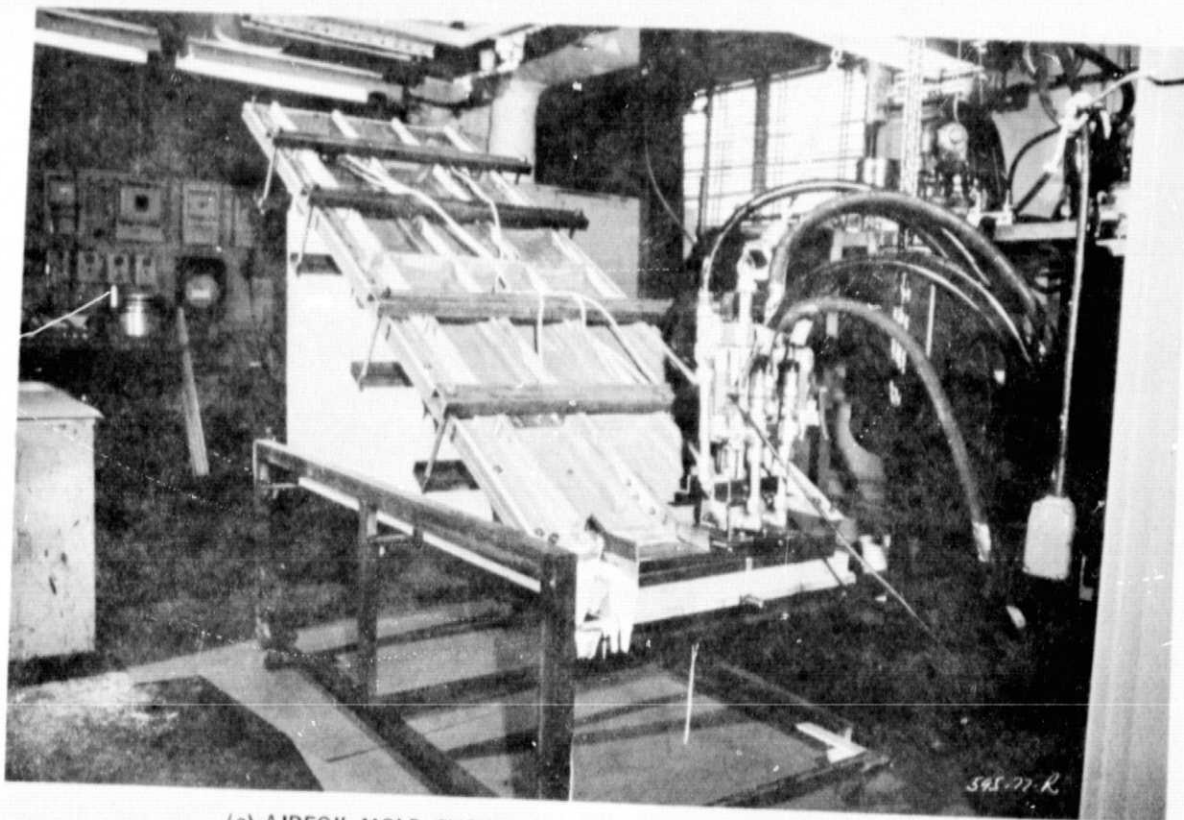
Figure 6. - Continued.

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(c) SPAR MANUFACTURING CONCEPT.
Figure 6. - Concluded.

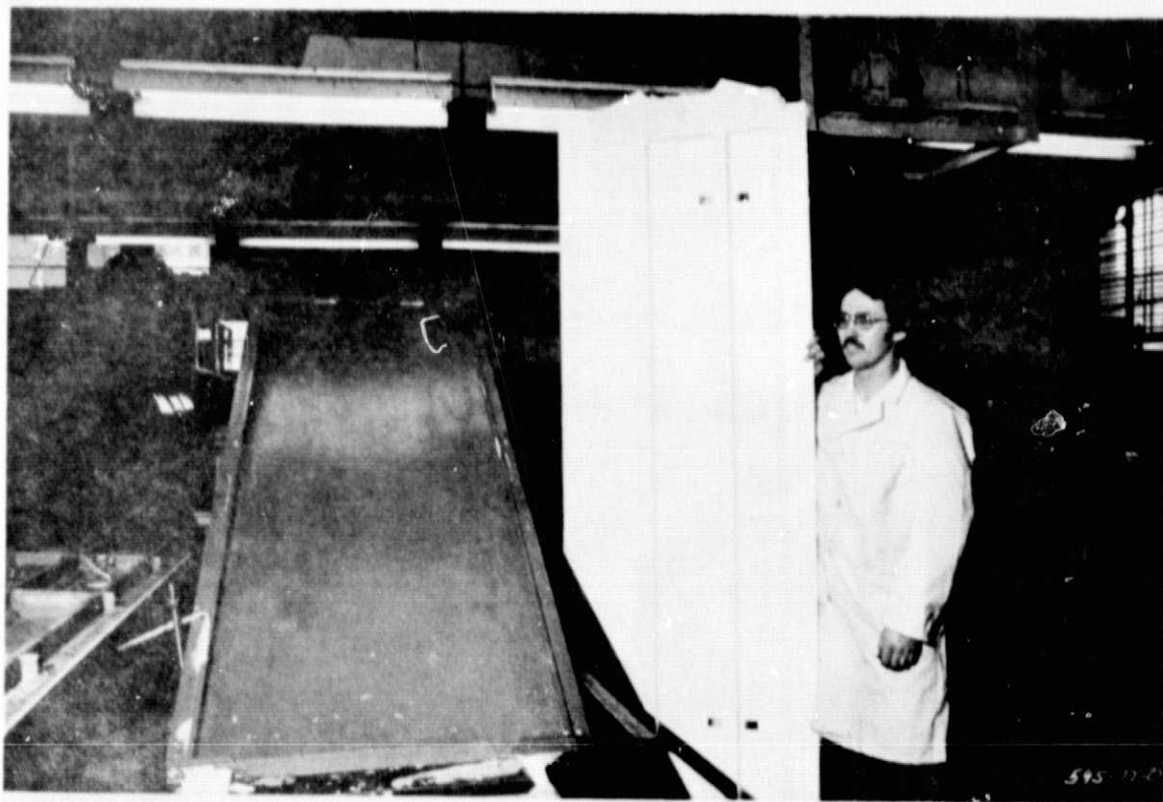
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(a) AIRFOIL MOLD SHOWING INJECTION HEAD AT BASE OF UNIT.

Figure 7. - Urethane blade segment manufacture.

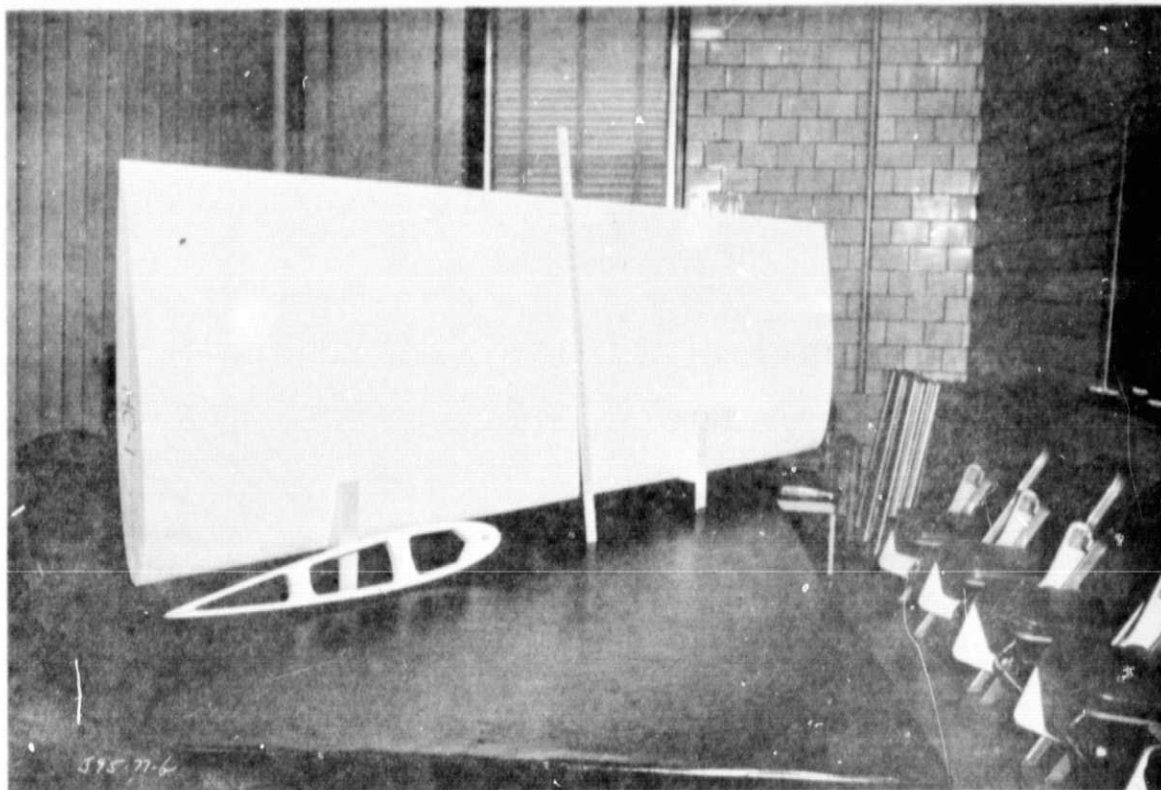
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(b) MOLD AND SEGMENT HALF SECTION.

Figure 7. - Continued.

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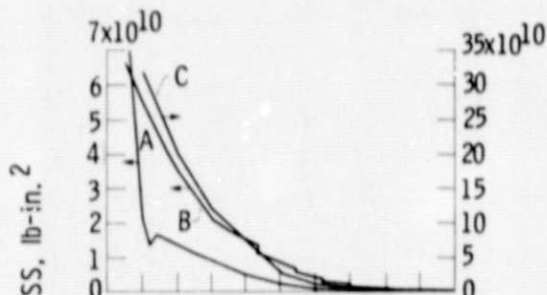


(c) COMPLETED CAST BLADE SEGMENT.

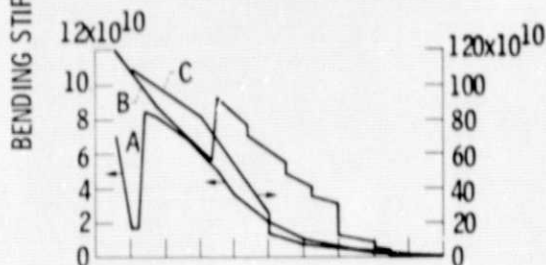
Figure 7. - Concluded.

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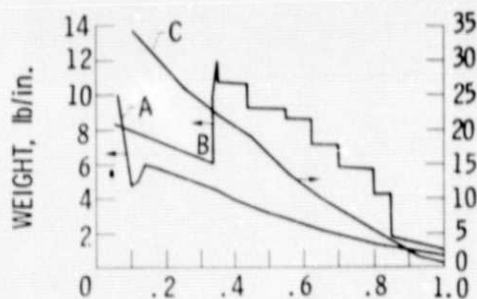
BLADE	LENGTH, ft	MATERIAL
A	60	GLASS/EPOXY
B	60	PRESTRESSED CONCRETE
C	150	GLASS/EPOXY



(a) FLATWISE BENDING STIFFNESS.

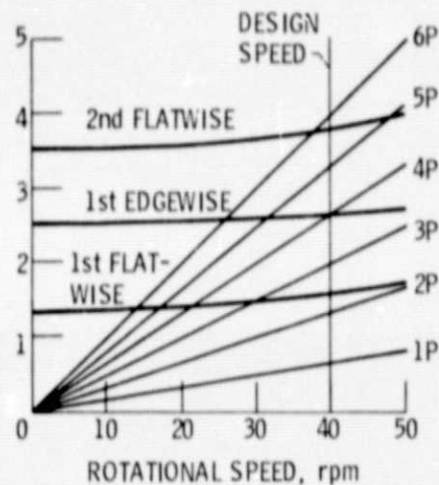


(b) CHORDWISE BENDING STIFFNESSES.

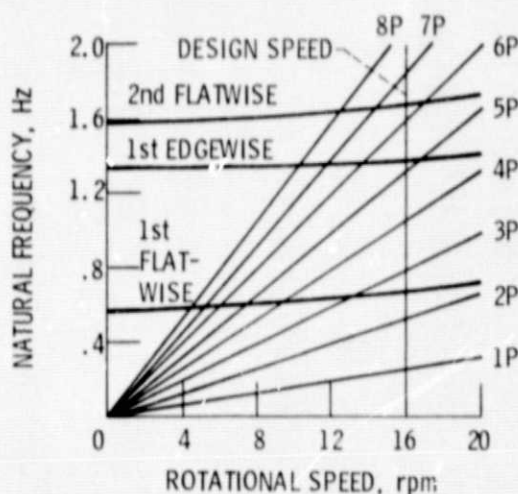


(c) SPANWISE WEIGHT DISTRIBUTION.

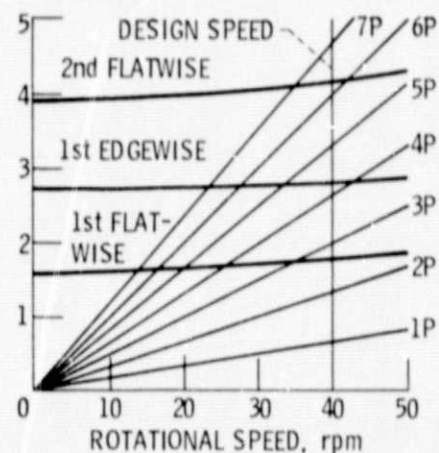
Figure 8. - Stiffness and weight distributions for WTG blades.



(a) 60-foot FIBERGLASS/EPOXY BLADE.



(b) 150-foot FIBERGLASS/EPOXY BLADE.



(c) 60-foot CONCRETE BLADE.

Figure 9. - WTG blade Campbell diagrams.

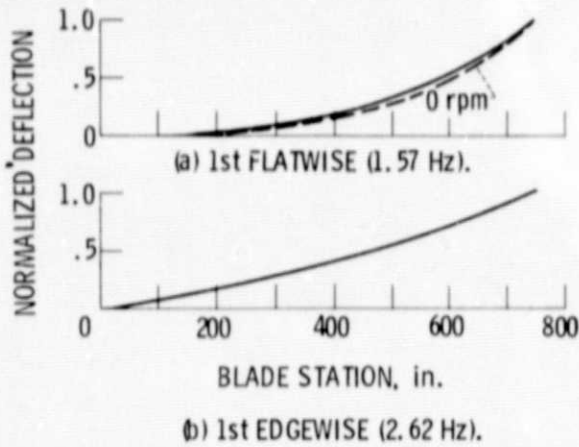


Figure 10. - 60-Foot composite blade predicted vibration mode shapes (40 rpm rotational speed).

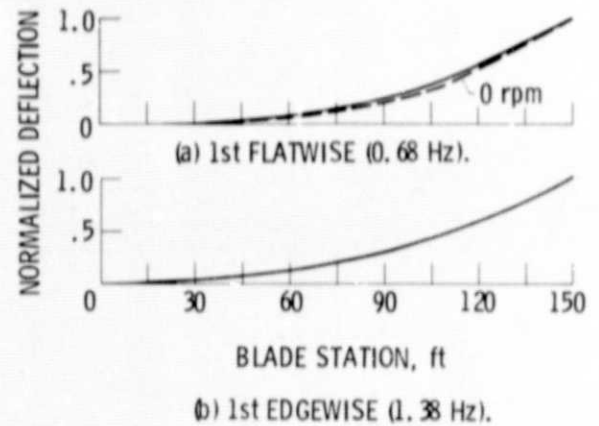


Figure 11. - 150-Foot composite blade vibration mode shapes (16 rpm rotational speed).

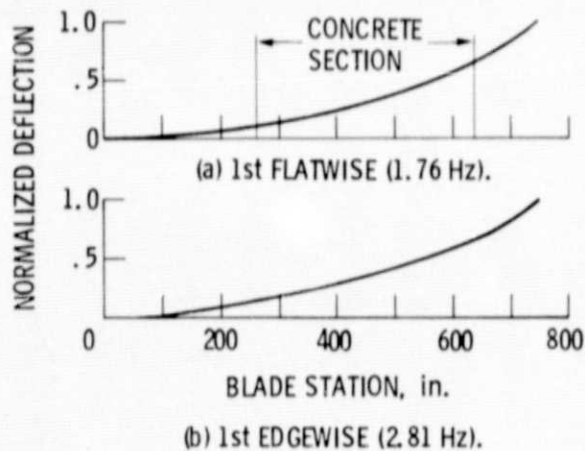


Figure 12. - 60-Foot concrete blade vibration mode shapes (40 rpm rotational speed).

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